APPENDIX B:

EVALUATION OF LEVEE FRAGILITY

- **Liquefaction Mode of Failure**
- **Non-Liquefaction Deformation Mode of Failure**

APPENDIX B: EVALUATION OF LEVEE FRAGILITY

B1. GENERAL

This appendix presents more detailed information regarding the development of levee fragility estimates for potential levee failures due to future seismic events. The fragility estimates were previously described in general terms in Chapter 4. Many of the estimates were based on consensus judgements made by the sub-team members. Sub-team members applied their knowledge of the performance of similar earth structures to the conditions which currently exist in the Delta, and to the potential seismic loadings which might develop in the future. In addition, a number of geotechnical earthquake engineering analyses were also performed to provide information for these judgements, and to extend the estimates for a range of loadings.

The seismic risk analyses and assessments presented in this report are based on the most current available information. Information on the seismic response of peat/organic soils is still being developed. Also, even though hundreds of borings describing the subsurface conditions of Delta levees were reviewed, these borings can only provide a limited characterization of the hundreds of miles of levees in the Delta. It does not appear likely that additional borings will significantly change the present characterization in the near future.

B2. DAMAGE POTENTIAL ZONES

As previously described in Chapter 4, the central portion of the Delta was divided into four Damage Potential Zones in order to allow for different levels of levee fragility in different areas of the Delta (see Figure 4-1). The criteria used for establishing the zoning was discussed previously in Chapter 4. The four zones encompass essentially all of the Delta land which lies below sea level and includes approximately 660 levee miles. Another 440 miles of levee exist at higher elevations within the legal limits of the Delta, but were not included because these levees retain significant depths of water only during flood season. Table B-1 summarizes the Delta islands and tracts included in the four zones along with the lengths of levees to be found in each zone.

B3. ESTIMATES OF LIQUEFACTION-INDUCED LEVEE FAILURES

The sub-team gathered data from borings and CPT soundings to establish "typical" conditions at a number of representative levee reaches throughout the Delta. Data from prior seismic fragility studies, DWR data, and data supplied by individual sub-team members were all reviewed. Liquefaction potential (i.e. resistance to "triggering" or

TABLE B-1: DELTA ISLANDS AND LEVEE LENGTHS CONSIDERED IN EVALUATING POTENTIAL EARTHQUAKE-INDUCED LEVEE FAILURE

Damage Potential Zone	Delta Island/ Reclamation District	Project Levee[1] (miles)	Non-Project[1] Levee (miles)	Total Levee Length[1] (miles)
I	Sherman	9.7	9.8	19.5 [19.5]
II	Bacon		14.3	14.3
	Bethel		11.5	11.5
	Bouldin		18.0	18.0
	Bradford		7.4	7.4
	Brannan	9.3	10.1	19.4
	Empire		10.5	10.5
	Holland		10.9	10.9
	Jersey		15.6	15.6
	Lower Jones		8.8	8.8
	Lower Roberts		16.0	16.0
	Mandeville		14.3	14.3
	McDonald		13.7	13.7
	Medford		5.9	5.9
	Orwood		10.9	10.9
	Palm		7.5	7.5
	Quimby		7.0	7.0
	Rindge		15.7	15.7
	Staten		25.4	25.4
	Twitchell	2.5	9.3	11.8
	Tyler	12.2	10.7	22.9
	Venice		12.3	12.3
	Webb		12.8	12.8
	Woodward		8.8	8.8 [301.4]
III	Byron		9.7	9.7
	Coney		5.4	5.4
	Fabian		18.8	18.8
	Hotchkiss		6.3	6.3
	Middle Roberts	6.1	3.7	9.8
	Rough and Ready		5.5	5.5
	Union	1.0	29.2	30.2
	Upper Jones		9.3	9.3
	Veale		5.7	5.7
	Victoria		15.1	15.1 [115.8]
IV	Andrus	10.0		10.0
	Bishop		5.8	5.8
	Brack		10.8	10.8
	Canal Ranch		7.5	7.5
	Dead Horse		2.6	2.6
	Grand	29.0		29.0
	Hastings	4.0	1.0	5.0
	King		9.0	9.0
	Liberty Island	9.0	9.0	18.0
	McCormack-Williamson		8.8	8.8
	New Hope		18.6	18.6
	Pierson	10.0		10.0
	Prospect	7.0	5.0	12.0
	Rio Blanco		4.0	4.0
	Ryer	20.6		20.6
	Sacramento Co.	2.0	5.0	7.0
	Shima		6.6	6.6
	Sutter	12.5		12.5
	Terminous		16.1	16.1
	Walnut Grove	1.0	1.2	2.2
	Wright Elmwood		6.8	6.8 [222.9]
				[659.6]Miles

1 Levee lengths listed in Sacramento-San Joaquin Delta Atlas, DWR (1993)

initiation of liquefaction) for sandy and silty soils of low plasticity was evaluated using the SPT-based methodology described by Seed and Harder (1990), as updated by the NCEER Liquefaction Workshop expert panel (NCEER, 1997). Of particular concern to the sub-team was the presence of cohesionless sandy and/or silty soils within the manmade levee embankment. When present, such soils often had SPT $(N_1)_{60}$ blowcounts of less than 10, and commonly less than 5. Post-liquefaction residual strengths were estimated using the correlation proposed by Seed and Harder (1990), and these indicated very low values, commonly only about 50 to 200 psf. With such low residual shear strengths, major levee displacements and/or failure would be expected if major portions of the levee embankment were triggered to liquefy.

Of somewhat lesser concern, but still potentially serious, was the occurrence of potentially liquefiable sandy and silty soils in the foundation zone (beneath the levee embankments). These soils tended to have variable SPT blowcounts, but generally somewhat higher than those in the loose embankment soils. The liquefiable foundation soils were also less hazardous due to levee and foundation geometries, as well as due to the irregular and discontinuous nature of some of these natural foundation deposits. Potential liquefaction of foundation soils was not a benign condition, however, and liquefaction of foundation soils was eventually judged to contribute approximately 25% to 30% of the overall liquefaction-related hazard (with liquefaction of levee embankment fills contributing the remainder.)

The sub-team worked together to assemble and review the available geotechnical data. Each of the individuals then prepared independent assessments of expected levee failure frequencies for various levels of shaking within each of the four Damage Potential Zones. These individual assessments, and their basis, were then shared and discussed to develop a single set of overall consensus estimates. These consensus estimates of potential number of levee failures were presented as a range for each level of shaking and for each of the four Damage Potential Zones. Each range was considered to represent about an 80-percent confidence level for the range of "expected" number of liquefaction-induced levee failures for a particular level of shaking.

B4. ESTIMATES OF LEVEE FAILURES FOR NON-LIQUEFACTION EARTHQUAKE-INDUCED DISPLACEMENTS

Based on Newmark-type cyclic inertial deformation analyses for a range of levels of static (non-seismic) stability, the sub-team concluded that any levee reaches which might fail without major strength losses such as liquefaction would have to be only marginally stable during static conditions. The effect of seismic shaking would be to either trigger or induce deformations as a result of inertial effects. To estimate the number of failures associated with a non-liquefaction deformation mode of failure, the sub-team proceeded in the following steps:

1. The number of marginally stable levee sites in each Damage Potential Zone was first estimated based on the experience of the sub-team members in dealing with problem sites. Three levels of marginal stability were considered. The estimated numbers of potentially marginal sites in each zone are listed in Table B-2. Also presented in Table B-2 are the estimated ranges of yield acceleration, k_y, for each level of marginal stability (k_y is the level of acceleration at which yielding and onset of permanent deformations will occur).

2. Estimates of earthquake-induced deformations were calculated using the Newmark double-integration method for a selected number of accelerograms. Seven accelerograms were selected to provide a reasonable range of duration and frequency content characteristics representative of the levels of seismic excitation being considered (M~5 to 7). These records from "stiff soil" or "rock" sites were then modified by means of site response analyses, using computer program SHAKE91 (Idriss et al., 1991), to develop motions representative of typical Delta levee embankment and foundation soil conditions. The base accelerograms were input as outcrop motions at a stiff soil base layer and then propagated through a deep Delta soil profile up to the surface of the levee. Near-surface motions (at the bases of potential deformation zones) were then scaled to different peak accelerations, and these were then double-integrated to obtain displacements for a range of yield accelerations. An allowance was made to account for spatial and temporal incoherence across a potential slide mass or deformation zone. Figure B-1 and Table B-3 present the results of these calculations. For the purposes of relating probabilistic base accelerations developed in Chapter 3 to a deformation mode of failure, the following was assumed:

    - The base acceleration would be amplified through soft Delta deposits by a factor of 1.6. Thus, a "stiff soil" acceleration of 0.1g would lead to a peak acceleration of 0.16g at the crown of the levee.

    - The average peak acceleration of a potential sliding mass would be approximately 40 percent of the levee crown acceleration. This is based on the work by Makdisi and Seed (1977) and assuming that the marginal sites have relatively deep potential sliding surfaces.

    - Thus, the average acceleration of potential sliding surface, k_{max}, is approximately 65 percent of the base acceleration of a stiff soil outcrop motion [$1.6 \times 0.4 \approx 0.65$].

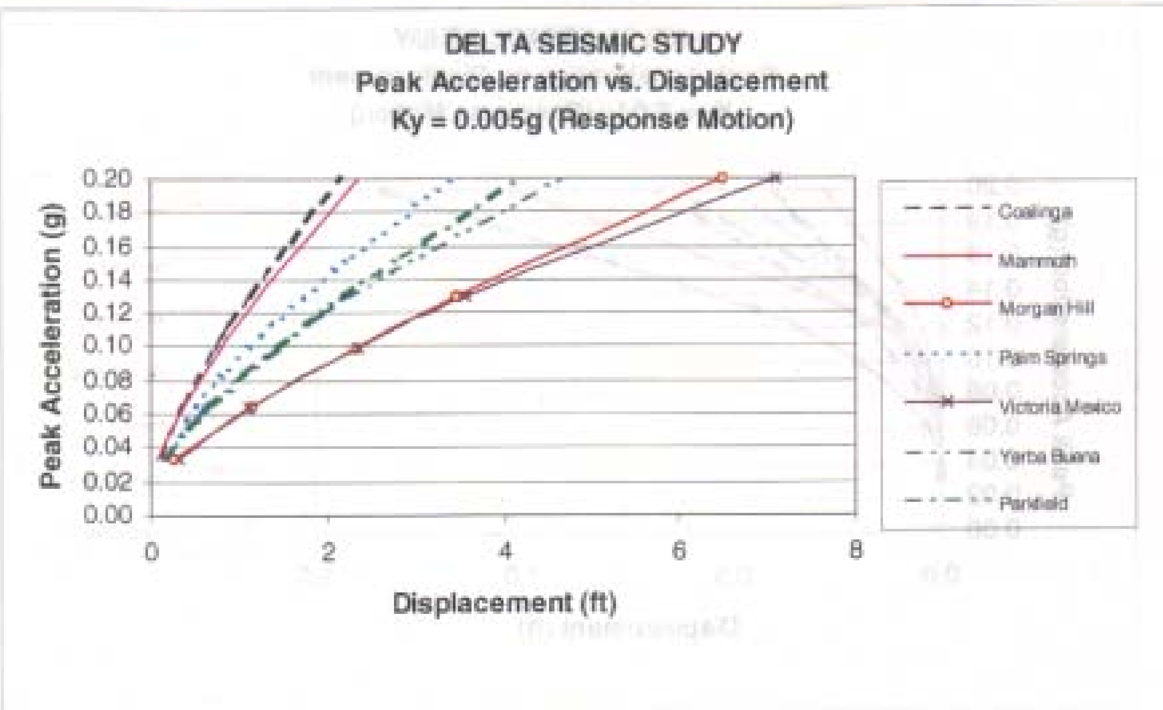
TABLE B-2: ESTIMATED NUMBER OF MARGINALLY STABLE LEVEE SITES IN NON-LIQUEFIED REACHES WITHIN DAMAGE ASSESSMENT ZONES

Stability Category	Approximate Yield Acceleration $k_y(g)$	Estimated Number of Sites in each Damage Potential Zone				
		Zone I (20 miles)	Zone II (301 miles)	Zone III (116 miles)	Zone IV (223 miles)	Total (660 miles)
A	0.00 - 0.01	1 - 2	6 - 12	0.3 - 2	0.7 - 3	8 - 19
B	0.01 - 0.03	1 - 3	12 - 24	0.7 - 3	1.3 - 7	15 - 37
C	0.03 - 0.05	3 - 8	20 - 60	1.7 - 5	3.3 - 10	28 - 83

TABLE B-3: ESTIMATED EARTHQUAKE-INDUCED DISPLACEMENTS IN NON-LIQUEFIED REACHES WITHIN DAMAGE ASSESSMENT ZONES

Magnitude 6.0 Bedrock/Stiff Soil Peak Acceleration (g)	Average Peak Acceleration[1] $k_{max}(g)$	Earthquake-Induced Displacement for Stability Categories[2]		
		A (k_y=0.005g)	B (k_y=0.02g)	C (k_y=0.04g)
0.05	0.033	0.1 - 0.3 ft [0.2 ft.]	0.0 - 0.0 ft. [0.1 ft.]	0.0 - 0.0 ft. [0.1 ft.]
0.10	0.065	0.3 - 1.1 ft [0.6 ft.]	0.1 - 0.2 ft. [0.1 ft]	0.0 - 0.0 ft. [0.1 ft.]
0.15	0.10	0.7 - 2.3 ft [1.4 ft]	0.1 -0.7 ft. [0.3 ft.]	0.0 - 0.2 ft. [0.1 ft.]
0.20	0.13	1.1 - 3.6 ft [2.2 ft]	0.3 - 1.2 ft. [0.6 ft.]	0.1 - 0.4 ft. [0.15 ft.]
0.30	0.20	2.2 - 7.1 [4.2 ft]	0.9 - 2.8 ft. [1.5 ft.]	0.3 - 1.4 ft. [0.6 ft.]

Notes: 1. Average Peak Acceleration assumed to be equal to 65 percent of the base bedrock/stiff soil motion.
2. Range and best estimate of earthquake-induced displacements calculated using the Newmark double-integration method.



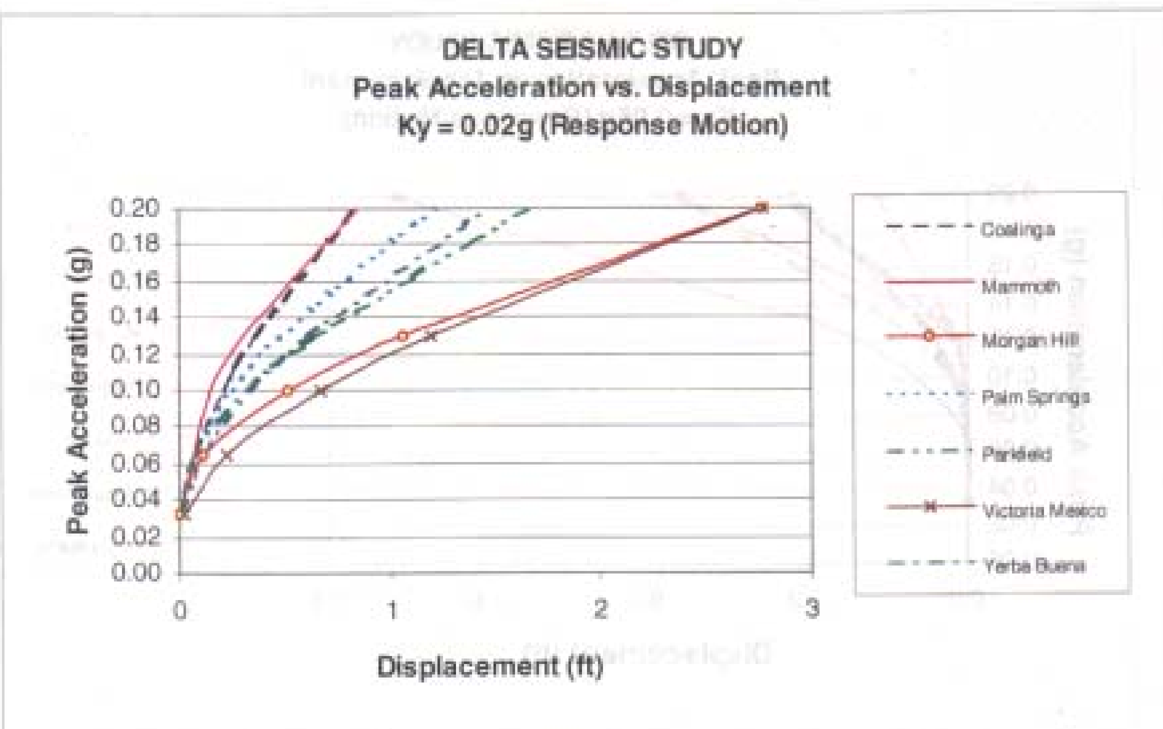
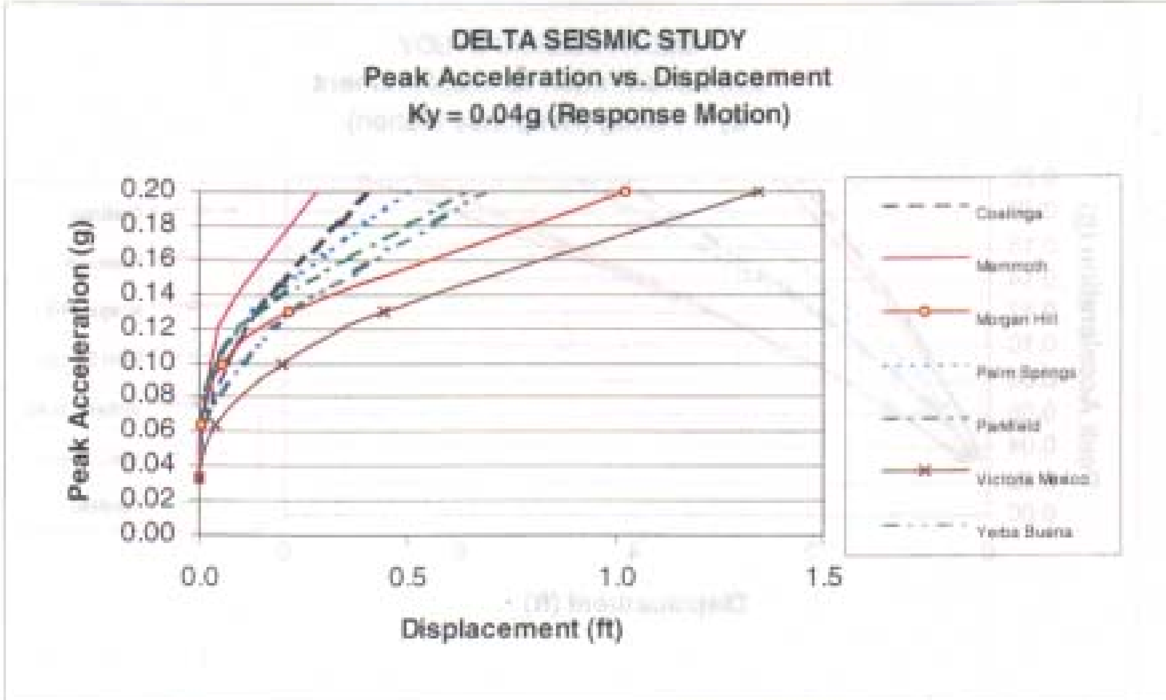


Figure B-1a: Range of Calculated Deformations for Selected Accelerograms



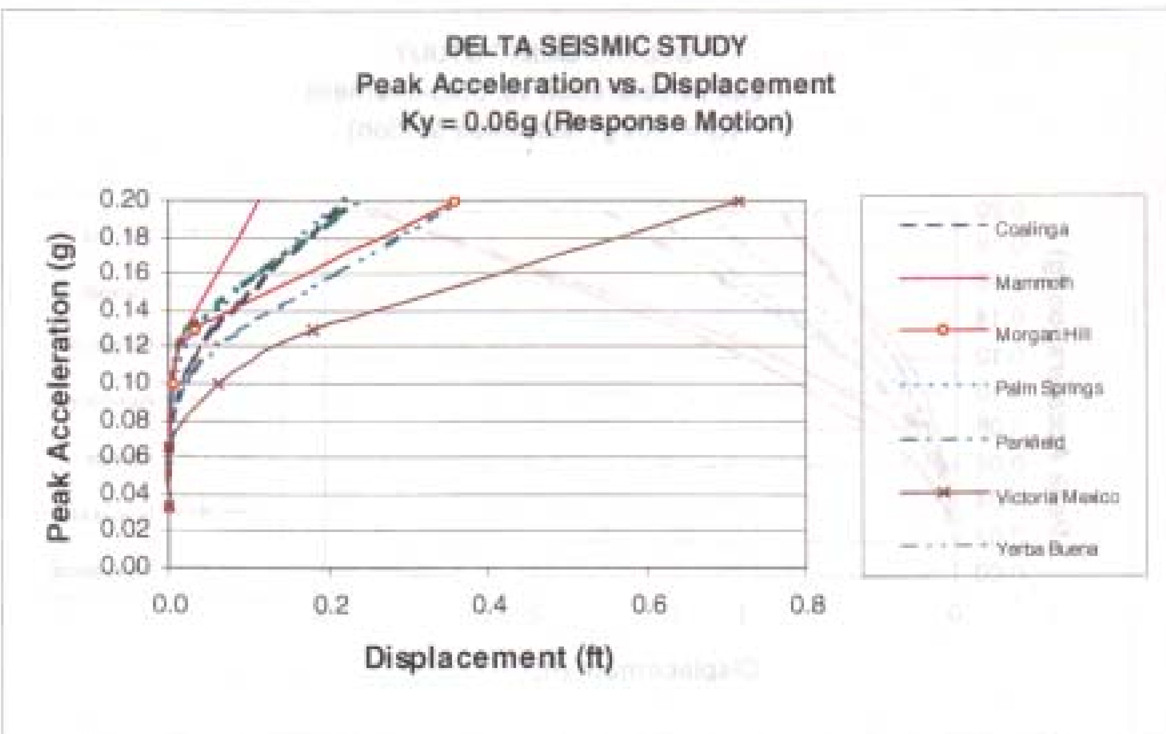


Figure B-1b: Range of Calculated Deformations for Selected Accelerograms

For the purposes of these evaluations, the median values of calculated displacement from the seven accelerograms were selected for use. This was judged to be representative of the cyclic inertial deformations expected to result from earthquakes of $M_w \approx 6$. For larger and smaller magnitudes, the induced deformations would be greater or smaller due to the longer or shorter durations of shaking (larger or smaller numbers of cycles of loading). Accordingly, these deformation estimates were later scaled for magnitude (duration) effects.

3. The estimated levee deformations were then converted into probabilities of failure using an approximate relationship developed by the sub-team based on their experience with static levee distress in the Delta (see Figure B-2 and Table B-4). As discussed previously, the hazard curve in Figure B-2 jointly accounts for the following issues and variables:

   a. cracking associated with various deformation levels,
   b. potential exacerbation of seepage problems due to cracking and slumping,
   c. potential overtopping,
   d. potential inboard toe and/or face erosion and piping, and
   e. varying outboard water levels in rivers and sloughs due to both daily tidal fluctuations, and seasonal flow variations.

4. The failure probabilities were then summed for the different levels of marginal stability within a Damage Potential Zone, and then totaled as the number of failures for the non-liquefaction deformation mode of failure (see Table B-5).

B5. ESTIMATED POTENTIAL NUMBER OF LEVEE FAILURES

The total number of potential levee failures for both liquefaction and non-liquefaction deformation modes of failure are presented in Table B-6 and Figure B-3. As may be noted in both places, the failure potential associated with liquefaction is far greater than that estimated for non-liquefaction failures. This is probably related to the relatively low magnitude and corresponding short duration of a typical Magnitude 6 earthquake. Accordingly, there are only a very small number of acceleration peaks which would exceed any particular yield acceleration.

B6. ESTIMATED POTENTIAL LEVEE FRAGILITY

It should also be noted that the estimated numbers of failures shown in Table B-6 and Figure B-3 assume that the entire Delta is shaken to the same level of earthquake motion (e.g. 0.2g). This is unrealistic as no one earthquake event will ever do this. A better way of representing the potential for failure is to normalize the estimated number of failures by levee length for each Damage Potential Zone. A normalized levee fragility can then be determined in the form of estimated number of failures per 100 miles of levee (these values were obtained by taking the values in Table B-6 and then dividing by the levee length in each zone and then multiplying by 100). The estimated levee fragility values for both liquefaction and non-liquefaction modes of failure, for causative events of $M_w \approx 6.0$, are shown in Table B-7.

SEISMIC STABILITY OF LEVEES IN THE SACRAMENTO - SAN JOAQUIN DELTA
PROBABILITY OF FAILURE ASSOCIATED WITH EARTHQUAKE-INDUCED DISPLACEMENTS

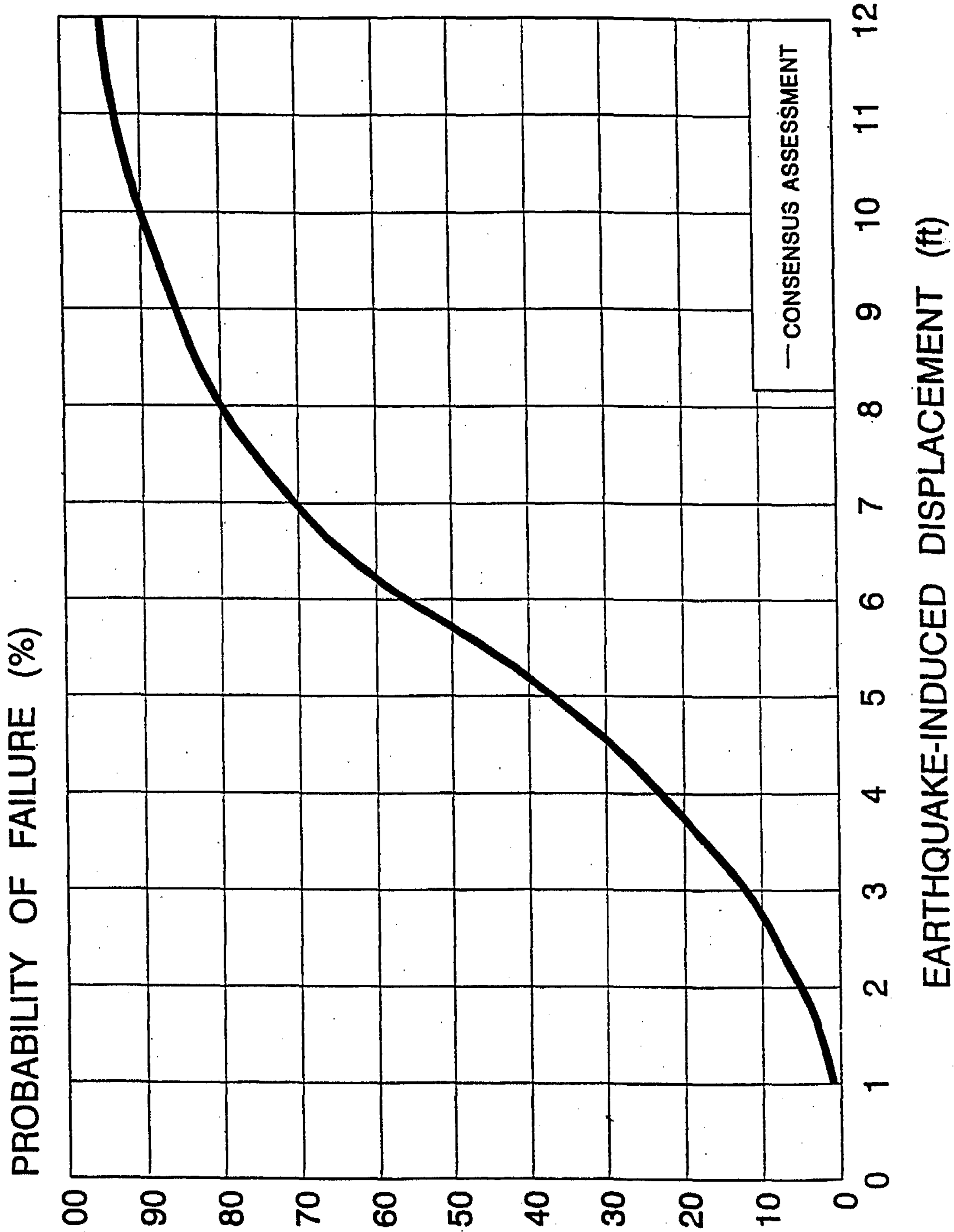


FIGURE B-2: PROBABILITY OF FAILURE ASSOCIATED WITH EARTHQUAKE-INDUCED DISPLACEMENTS

TABLE B-4: ESTIMATED PROBABILITIES OF LEVEE FAILURE ASSOCIATED WITH EARTHQUAKE-INDUCED DISPLACEMENTS IN NON-LIQUEFIED REACHES

Magnitude 6.0 Bedrock/Stiff Soil Peak Acceleration (g)	Average Peak Acceleration[1] k_{max}(g)	Estimated Probability of Levee Failure for Stability Categories[2]		
		A (k_y=0.005g)	B (k_y=0.02g)	C (k_y=0.04g)
0.05	0.033	**0.2%** [0.2 ft.]	**0.1%** [0.1 ft.]	**0.1%** [0.1 ft.]
0.10	0.065	**0.6%** [0.6 ft.]	**0.1%** [0.1 ft]	**0.1%** [0.1 ft.]
0.15	0.10	**2.6%** [1.4 ft]	**0.3%** [0.3 ft.]	**0.1%** [0.1 ft.]
0.20	0.13	**6.0%** [2.2 ft]	**0.6%** [0.6 ft.]	**0.2%** [0.15 ft.]
0.30	0.20	**25.0%** [4.2 ft]	**3.0%** [1.5 ft.]	**0.6%** [0.6 ft.]

Notes: 1. Average Peak Acceleration assumed to be equal to 65 percent of the base bedrock/stiff soil motion.
2. Estimated Probability of Levee Failure for non-liquefied levees based on estimated earthquake-induced deformations calculated using the Newmark method (see Table B-3).

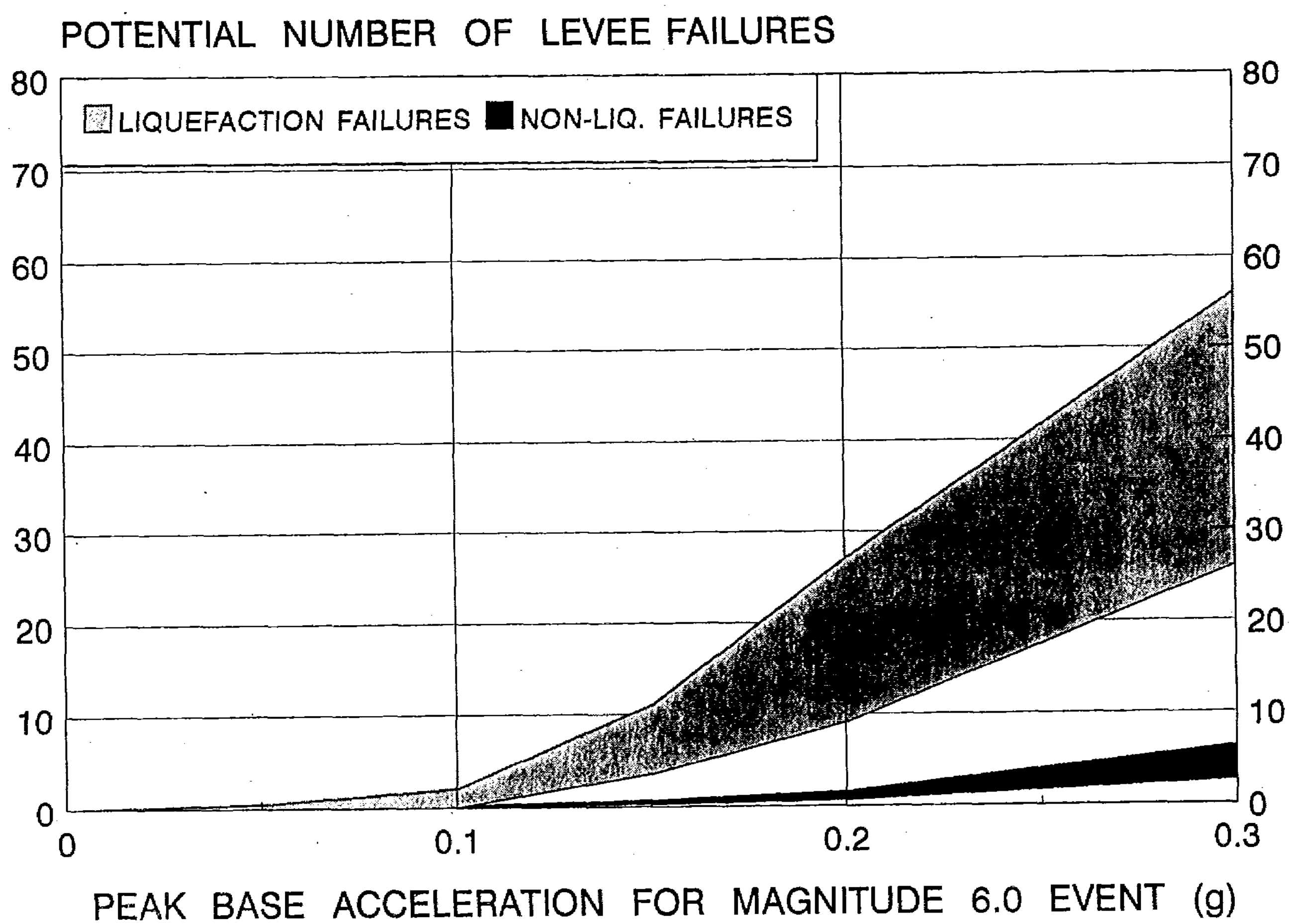
TABLE B-5: ESTIMATED NUMBER OF LEVEE FAILURES ASSOCIATED WITH EARTHQUAKE-INDUCED DISPLACEMENTS IN NON-LIQUEFIED REACHES

Magnitude 6.0 Rock/Stiff Soil Peak Acc. (g)	Damage Potential Zone	Levee Length (miles)	Estimated Number of Levee Failures in Non-Liquefied Reaches		Estimated Failure Rate (Fragility) Failures per 100 miles
0.05	I	20	[1x0.002+1x0.001+3x0.001]-[2x0.002+3x0.001+8x0.001]=	**0.006 - 0.015**	**0.030 - 0.075**
	II	301	[6x0.002+12x0.001+20x0.001]-[12x0.002+24x0.001+60x0.001]=	**0.044 - 0.108**	**0.015 - 0.036**
	III	116	[0.3x0.002-0.7x0.001+1.7x0.001]-[2x0.002+3x0.001+5x0.001]=	**0.003 - 0.012**	**0.003 - 0.010**
	IV	223	[0.7x0.002+1.3x0.001+3.3x0.001]-[3x0.002+7x0.001+10x0.001]=	**0.006 - 0.023**	**0.003 - 0.010**
0.10	I	20	[1x0.006+1x0.001+3x0.001]-[2x0.006+3x0.001+8x0.001]=	**0.010 - 0.023**	**0.050 - 0.12**
	II	301	[6x0.006+12x0.001+20x0.001]-[12x0.006+24x0.001+60x0.001]=	**0.068 - 0.156**	**0.023 - 0.052**
	III	116	[0.3x0.006+0.7x0.001+1.7x0.001]-[2x0.006+3x0.001+5x0.001]=	**0.004 - 0.020**	**0.004 - 0.017**
	IV	223	[0.7x0.006+1.3x0.001+3.3x0.001]-[3x0.006+7x0.001+10x0.001]=	**0.009 - 0.035**	**0.004 - 0.016**
0.15	I	20	[1x0.026+1x0.003+3x0.001]-[2x0.026+3x0.003+8x0.001]=	**0.032 - 0.069**	**0.16 - 0.35**
	II	301	[6x0.026+12x0.003+20x0.001]-[12x0.026+24x0.003+60x0.001]=	**0.212 - 0.444**	**0.070 - 0.15**
	III	116	[0.3x0.026+0.7x0.003+1.7x0.001]-[2x0.026+3x0.003+5x0.001]=	**0.012 - 0.066**	**0.010 - 0.057**
	IV	223	[0.7x0.026+1.3x0.003+3.3x0.001]-[3x0.026+7x0.003+10x0.001]=	**0.025 - 0.109**	**0.011 - 0.049**
0.20	I	20	[1x0.060+1x0.006+3x0.002]-[2x0.060+3x0.006+8x0.002]=	**0.072 - 0.154**	**0.36 - 0.77**
	II	301	[6x0.060+12x0.006+20x0.002]-[12x0.060+24x0.006+60x0.002]=	**0.472 - 0.984**	**0.16 - 0.33**
	III	116	[0.3x0.060+0.7x0.006+1.7x0.002]-[2x0.060+3x0.006+5x0.002]=	**0.026 - 0.148**	**0.022 - 0.13**
	IV	223	[0.7x0.060+1.3x0.006+3.3x0.002]-[3x0.060+7x0.006+10x0.002]=	**0.056 - 0.242**	**0.025 - 0.11**
0.30	I	20	[1x0.250+1x0.030+3x0.006]-[2x0.250+3x0.030+8x0.006]=	**0.298 - 0.638**	**1.5 - 3.2**
	II	301	[6x0.250+12x0.030+20x0.006]-[12x0.250+24x0.030+60x0.006]=	**1.980 - 4.080**	**0.66 - 1.4**
	III	116	[0.3x0.250+0.7x0.030+1.7x0.006]-[2x0.250+3x0.030+5x0.006]=	**0.106 - 0.620**	**0.092 - 0.53**
	IV	223	[0.7x0.250+1.3x0.030+3.3x0.006]-[3x0.250+7x0.030+10x0.006]=	**0.234 - 1.020**	**0.11 - 0.46**

TABLE B-6: ESTIMATED NUMBER OF FAILURES FOR BOTH LIQUEFIED AND NON-LIQUEFIED REACHES

Magnitude 6.0 Rock/Stiff Soil Peak Acc. (g)	Damaged Potential Zone	Levee Length (miles)	Estimated Number of Levee Failures		
			Liquefied Reaches	Non-Liq. Reaches	Total
0.05	I	20	0 - 0.13	0.01 - 0.02	**0.01 - 0.15**
	II	301	0 - 0.25	0.04 - 0.11	**0.04 - 0.36**
	III	116	0 - 0.03	0 - 0.01	**0 - 0.04**
	IV	223	0 - 0.07	0.01 - 0.02	**0.01 - 0.09**
	Total	**660**	**0 - 0.48**	**0.06 - 0.16**	**0.06 - 0.64**
0.10	I	20	0 - 0.5	0.01 - 0.02	**0.01 - 0.52**
	II	301	0 - 1.0	0.07 - 0.16	**0.07 - 1.16**
	III	116	0 - 0.2	0 - 0.02	**0 - 0.22**
	IV	223	0 - 0.3	0.01 - 0.04	**0.01 - 0.34**
	Total	**660**	**0 - 2**	**0.09 - 0.24**	**0.09 - 2.24**
0.15	I	20	0.5 - 2	0.03 - 0.07	**0.53 - 2.07**
	II	301	2 - 5	0.21 - 0.44	**2.21 - 5.44**
	III	116	0.3 - 1.4	0.01 - 0.07	**0.31 - 1.47**
	IV	223	0.7 - 2.6	0.03 - 0.11	**0.73 - 2.71**
	Total	**660**	**3.5 - 11**	**0.28 - 0.69**	**3.78 - 11.69**
0.20	I	20	1 - 4	0.07 - 0.15	**1.07 - 4.15**
	II	301	5 - 15	0.47 - 0.98	**5.47 - 15.98**
	III	116	1 - 3	0.03 - 0.15	**1.03 - 3.15**
	IV	223	2 - 5	0.06 - 0.24	**2.06 - 5.24**
	Total	**660**	**9 - 27**	**0.63 - 1.52**	**9.63 - 28.52**
0.30	I	20	3 - 6	0.30 - 0.64	**3.30 - 6.64**
	II	301	15 - 30	1.98 - 4.08	**16.98 - 34.08**
	III	116	3 - 7	0.11 - 0.62	**3.11 - 7.62**
	IV	223	5 - 13	0.23 - 1.02	**5.23 - 14.02**
	Total	**660**	**26 - 56**	**2.62 - 6.36**	**28.62 - 62.36**

SEISMIC STABILITY OF LEVEES IN THE SACRAMENTO - SAN JOAQUIN DELTA
ASSESSMENT OF POTENTIAL NUMBER OF LEVEE FAILURES



Note: Assessment assumes that the entire Delta area is shaken by the postulated earthquake shaking

FIGURE B-3: ESTIMATED NUMBER OF LEVEE FAILURES FOR DIFFERENT LEVELS OF EARTHQUAKE SHAKING

TABLE B-7: ESTIMATED FAILURE RATE (FRAGILITY) FOR BOTH LIQUEFIED AND NON-LIQUEFIED REACHES - FAILURES PER 100 MILES

Magnitude 6.0 Rock/Stiff Soil Peak Acc. (g)	Damaged Potential Zone	Levee Length (miles)	Estimated Fragility - Number of Levee Failures per 100 miles	
			Liquefied Reaches	Non-Liq. Reaches
0.05	I	20	0.005 - 0.50	0.030 - 0.075
	II	301	0.001 - 0.083	0.015 - 0.036
	III	116	0.001 - 0.033	0.003 - 0.010
	IV	223	0.001 - 0.033	0.003 - 0.010
0.10	I	20	0.20 - 2.5	0.050 - 0.12
	II	301	0.080 - 0.33	0.023 - 0.052
	III	116	0.050 - 0.15	0.004 - 0.017
	IV	223	0.050 - 0.15	0.004 - 0.016
0.15	I	20	2.5 - 10.	0.16 - 0.35
	II	301	0.66 - 1.7	0.070 - 0.15
	III	116	0.29 - 1.2	0.010 - 0.057
	IV	223	0.29 - 1.2	0.011 - 0.049
0.20	I	20	5. - 20.	0.36 - 0.77
	II	301	1.7 - 5.0	0.16 - 0.33
	III	116	0.88 - 2.3	0.022 - 0.13
	IV	223	0.88 - 2.3	0.025 - 0.11
0.30	I	20	15. - 30.	1.5 - 3.2
	II	301	5.0 - 10.	0.66 - 1.4
	III	116	2.4 - 5.9	0.092 - 0.53
	IV	223	2.4 - 5.9	0.11 - 0.46

B7. MAGNITUDE CORRECTION FACTORS

The estimates for levee failures and fragility presented in the previous tables are for earthquake shaking associated with a magnitude 6.0 event. For the same level of shaking, larger earthquake magnitudes will induce more damage and levee failures than smaller events because larger magnitude earthquakes have longer durations and larger numbers of strong cycles of shaking. To adjust the fragilities for earthquake magnitudes other than Magnitude 6.0, the following corrections were used:

A. Liquefaction Mode of Failure:

A magnitude correction factor for the liquefaction mode of failure was developed using the Idriss (1997) magnitude scaling factors for triggering liquefaction. These corrections are slightly larger than those previously used by Seed et al. (1984).

B. Non-Liquefaction Deformation Mode of Failure:

A magnitude correction factor for the non-liquefaction deformation mode of failure was developed using the Earthquake Severity Index described by Bureau et al. (1988). This correction is much larger than the one for liquefaction, but is comparable with the deformation results obtained by Makdisi and Seed (1977).

For both failure modes (liquefaction, and non-liquefaction cyclic inertial deformation), the principal fragility estimates (Table B-7) were developed for events of $M_w \approx 6.0$, as that was central to the range of magnitudes principally contributing to the overall risk for the Delta. Figure B-4 shows the magnitude correction factors used for both modes of failure.

SEISMIC STABILITY OF DELTA LEVEES
MAGNITUDE CORRECTION FACTORS TO LEVEE FRAGILITY

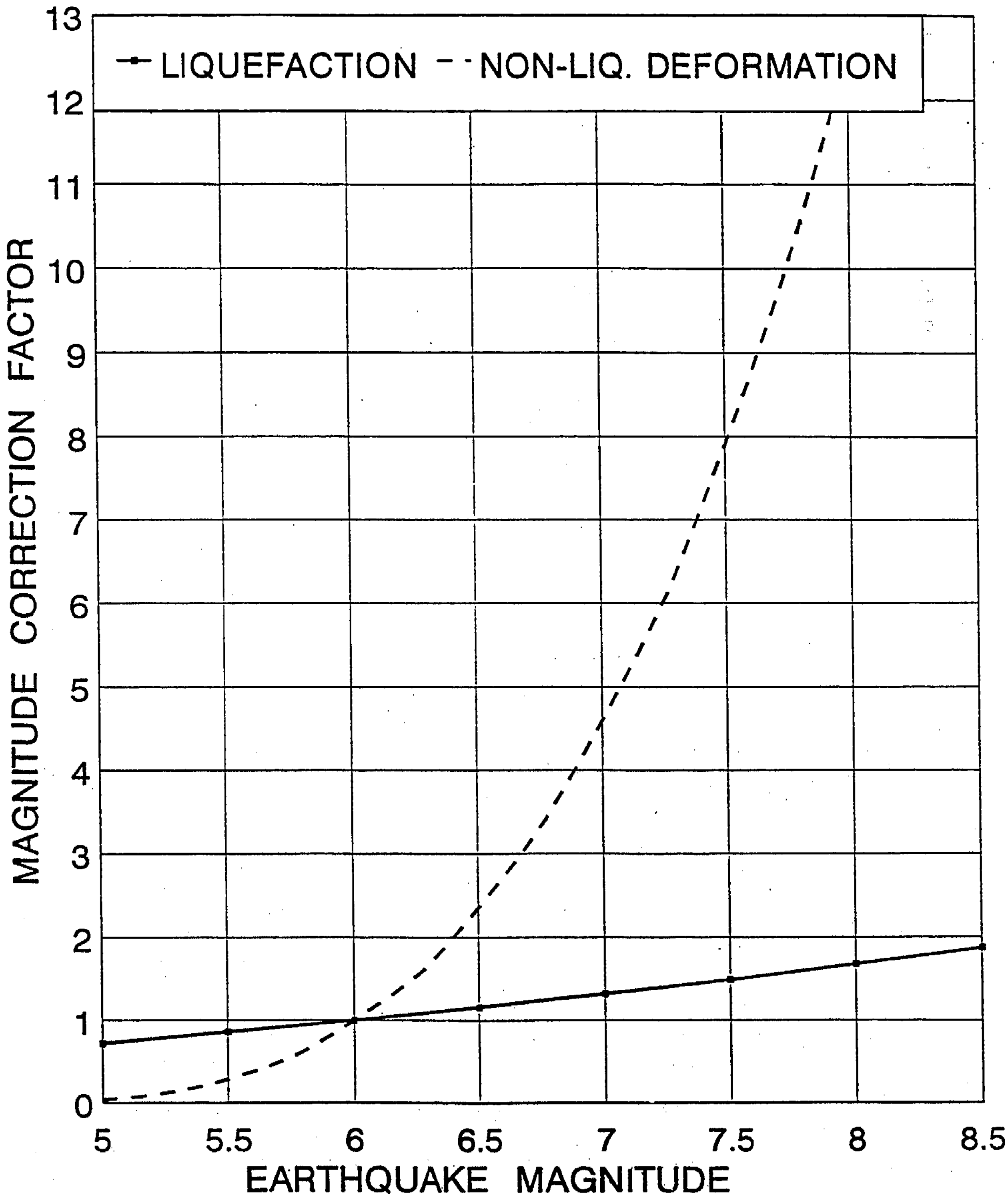


FIGURE B-4: MAGNITUDE CORRECTION FACTORS FOR LIQUEFACTION AND NON-LIQUEFACTION DEFORMATION MODES OF FAILURE